

Response to Reviewer 2:

This carefully prepared paper describes an Earth System model of intermediate complexity that captures Earth's C, N, P, O, and S cycles. The model is well-described and two relevant applications are presented to demonstrate the capabilities of the model. The model is particularly useful for simulations on long (geological) time scales. The model code is made available allowing the work to be reproduced (but see additional comment below).

I read this paper with pleasure and have relatively few comments. Most of the detailed comments below are suggestions to rephrase the text to improve the clarity. The manuscript is quite long but because it is well-written, I don't think that is a problem.

We are grateful to Reviewer 2 for the useful suggestions and comments, which have helped us to significantly improve our paper. As indicated in the responses that follow, we have taken all these comments and suggestions into account in the process of revision. We are pleased to say that the comments and suggestions have both greatly improved the quality of the manuscript.

Detailed comments

1. Lines 25 and 1650. The authors write that “The model source code is available on GitHub and represents a unique community tool” and later “The CANOPS-GRB code is provided freely but with the requirement that prospective users contact the corresponding author with their research plans...”. I don't think the latter requirement is appropriate. Other scientists should be free to use the model without the author's consent or knowledge. That's open science.

We agree. The sentence has been removed from the revised manuscript for the sake of open science.

2. Line 151. “preferred” instead of “required” since this will depend on the application.

Corrected.

3. Line 173. Suggested change: “of the Earth system”

Corrected.

4. Line 258: “to describe the overall design of the biogeochemical cycles”

Corrected.

5. Figure 2. caption needs editing. Line 267: “anaerobic” instead of “anoxygenic”

Corrected.

6. Line 278 and 283: “are transformed each other” needs rephrasing.

We have modified the corresponding sentences: “The abundance of inorganic nitrogen species (ammonium and nitrate), which are lumped into DIN (dissolved inorganic nitrogen), is affected by denitrification and nitrification.”, “The reservoir sizes of sedimentary sulfur (pyrite sulfur, *PYR*, and gypsum sulfur, *GYP*) and two sulfur species (SO_4^{2-} and $\Sigma\text{H}_2\text{S}$) in the ocean are controlled by volcanic outgassing, weathering, burial, MSR, AOM, and sulfide oxidation reactions.”

7. Line 312: change to “the water column”

Corrected.

8. Line 318. “2x60 sediment segments.” Can you explain why this is two times 60?

The ocean interior below the photic zone is divided into two sectors, HD and LD. The each sector is vertically subdivided into 60 layers. We have added a brief explanation about this (Line 329), and are grateful for the opportunity to clarify this point: “HD and LD have 60 layers, respectively”

9. Table 2: Better to use the term “Fe bound P” since a lot of the P is not sorbed and instead is more strongly bound.

Corrected.

10. Table 2: typo in “simulated” and “denitrification”

Corrected.

11. Line 344. AOM is more commonly referred to as “anaerobic oxidation of methane”

We agree and have thoroughly re-examined the use of the terms throughout the revised manuscript.

12. Line 345. “as a CH_4 degassing flux”

Corrected.

13. Line 399-401. There is more work that is relevant in this context. You could cite Algeo and Ingall (2007) since they clearly showed the role of hydrogen sulfide in P retention and/or Papadomanolaki et al. (2022; Science Advances) who show a potential role for acidification and warming.

We thank the reviewer for bringing these relevant papers to our attention. We referred these papers in the revised manuscript to better clarify this point.

14. Line 544: change to “papers”

Corrected.

15. Line 797. Here, methanogenesis is termed “organic matter production from carbon dioxide” whereas this is a degradation process. Needs to be reformulated.

Corrected.

16. Line 802: remove “most”

Corrected.

17. Line 803: You write: “oxidants for organic matter decomposition change gradually, depending on the amount of each oxidant”. Gradually with time? Or depth? Any change will also depend on the supply of reductants.

The reviewer is correct to point out that our original wording may be unclear as used in the original manuscript. We modified the sentence and are grateful for the opportunity provided by the reviewer to clarify this point: “The oxidants for organic matter decomposition change with the availability of each oxidant, which vary with time and water depth.”

18. Line 804: “on previous studies of early...”

Corrected.

19. Line 817: change to “in the geological past”

Corrected.

20. Line 821: “oxidation to” not “oxidation by”

Corrected.

21. Equation (32) remove the dot.

We keep the period to express the end of the sentence.

22. Line 831: change to “using a bimolecular..”

Corrected.

23. Line 834: by definition, the suboxic layer does not contain hydrogen sulfide so it would be better to reformulate.

The reviewer is correct to point out that our use of term of “suboxic layer” may be unclear. We corrected it to “chemocline”.

24. Line 844 Sentence needs reformulation for clarity

We deleted the sentence.

25. Line 858. Change to “are listed in”

Corrected.

26. Figure 6: the line corresponding to “This study (oxic)” is not visible in the figure.

Corrected.

27. Line 925. Here the authors write “such as” but it appears that these are the only terminal electron acceptors considered.

We deleted the sentence to avoid the confusion.

28. Line 960 See earlier comment on “Fe-sorbed P”

We have thoroughly re-examined the use of the terms “Fe-sorbed P” throughout the revised manuscript.

29. Line 1011-. Better to write “sediments overlain by oxic bottom waters”. This will only hold for sediments with a relatively low input of organic matter. Otherwise the Fe-bound P will be lost, as observed in many modern coastal sediments.

Corrected.

30. Line 1021-1025. See earlier comment.

We referred Papadomanolaki et al. paper in the revised manuscript.

31. Line 1270 change to “until reaching steady state”

Corrected.

32. Line 1291 change to “LD and HD regions”

Corrected.

33. Line 1380-1381. It’s not clear what is meant by “(Gray dots represent the unknown dissolved O₂ concentrations)”.

We modified the corresponding sentence, as follows: “The color represents the O₂ concentration of bottom water, [O₂]_{bw}, with grey dots for the unknown [O₂]_{bw} value.”

34. Figure 13b and lines 1404 and further. The authors focus on the benthic flux of P here but this gives a very large spread – as is commonly the case with benthic fluxes. No attempt was made to compile P burial fluxes from the literature. This needs some justification in the text, i.e. were there insufficient data to compare to or was there another reason?

This is a good point. The primary reason was a fact that the observation of the burial flux of reactive P is rare. We can find total P burial flux in the literature, but it is expected to contain detritus P, not bioavailable P. The sequestration methods, SEDEX, can distinguish reactive P from total P, but such observation is rare even in the modern ocean (as far as we know). To clarify this point, we added a sentence in the revised manuscript (Line 1369-1370): “The burial flux density of reactive P is not shown due to the sparseness of such observations.”

35. Lines 1450. Here you mention the role of the coastal ocean for N cycling. This is also relevant for the P cycle, since most P burial takes place in the coastal ocean. This could be mentioned somewhere in the text.

This is also a good point. We have recognized that the separate treatment of coastal sea from the open ocean affects the strength of the redox-dependent P feedback. We added a brief sentence for this (Line 1624-1625): “Further work will also be needed to better quantify the biogeochemical cycling in the continental shelf, which is a major locus of organic matter burial.” We also added a brief explanation in Line (1055-1057): “Given that the continental

shelves are a main locus of reactive P burial, the separate treatment of continental shelves and margin sediments from the pelagic ocean could affect the non-linearity of the redox-dependent P cycle. However, this was left as one of the subjects of future work.”

36. Line 1508. “...leads to a lower”

Corrected.

37. Line 1511. “leads”

Corrected.

Additional changes:

- Various minor changes in wording and corrections throughout the manuscript.

We hope that we have adequately addressed all the suggestions raised by Reviewer 2, and appreciate their constructive feedback.